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REVIEW

3D printing-assisted surgical planning versus traditional methods in complex liver resections: a systematic review

Planificación quirúrgica asistida por impresión 3D frente a métodos tradicionales en resecciones hepáticas complejas: una revisión sistemática

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ABSTRACT

Introduction: surgical resection remains a primary treatment for liver diseases, requiring precise preoperative planning due to the liver's complex anatomy. Traditional imaging techniques like CT and MRI provide essential information but have limitations in spatial visualization. The emergence of 3D-printed liver models (3DPLMs) offers a novel approach to improving surgical planning and outcomes.
Objective: this systematic review critically evaluates the outcomes of 3D printing assisted surgical planning versus traditional methods in complex liver resections.
Method: a comprehensive search was conducted in PubMed, Embase, and Web of Science, yielding 11 studies that met inclusion criteria. Data extraction focused on surgical planning accuracy, strategy modification, outcomes, and educational value.
Results: 3DPLMs improved surgical planning accuracy, with studies showing significant changes in surgical strategies in 16,7 % to 68 % of cases. Enhanced tumor detection rates, particularly for lesions ≤10 mm, were observed, improving pathological matching and staging. While 3DPLMs did not consistently reduce operative time or complications, they facilitated more precise resection proposals. Educationally, 3DPLMs increased satisfaction, comprehension, and surgical planning skills among trainees, outperforming traditional and virtual methods.
Conclusion: 3DPLMs enhance surgical planning accuracy, modify strategies, and improve educational outcomes in complex liver resections. Despite mixed impacts on intraoperative outcomes, their utility in preoperative planning and education is evident, warranting further exploration.

Keywords: 3D Printing; Liver Neoplasm; Liver Resection; Three-Dimensional Imaging; Tomography; X-Ray Computed (CT).

RESUMEN

Introducción: la resección quirúrgica sigue siendo un tratamiento primario para las enfermedades hepáticas, que requiere una planificación preoperatoria precisa debido a la compleja anatomía del hígado. Las técnicas de imagen tradicionales, como la tomografía computarizada y la resonancia magnética, proporcionan información esencial, pero tienen limitaciones en la visualización espacial. La aparición de modelos

hepáticos impresos en 3D (3DPLM) ofrece un enfoque novedoso para mejorar la planificación y los resultados quirúrgicos.
Objetivo: esta revisión sistemática evalúa críticamente los resultados de la planificación quirúrgica asistida por impresión 3D frente a los métodos tradicionales en resecciones hepáticas complejas.
Método: se realizó una búsqueda exhaustiva en PubMed, Embase y Web of Science, que arrojó 11 estudios que cumplieron con los criterios de inclusión. La extracción de datos se centró en la precisión de la planificación quirúrgica, la modificación de la estrategia, los resultados y el valor educativo.
Resultados: los 3DPLM mejoraron la precisión de la planificación quirúrgica, con estudios que mostraron cambios significativos en las estrategias quirúrgicas en el 16,7 % al 68 % de los casos. Se observaron tasas de detección de tumores mejoradas, en particular para lesiones ≤10 mm, lo que mejoró el emparejamiento patológico y la estadificación. Si bien los 3DPLM no redujeron sistemáticamente el tiempo quirúrgico ni las complicaciones, facilitaron propuestas de resección más precisas. Desde el punto de vista educativo, los 3DPLM aumentaron la satisfacción, la comprensión y las habilidades de planificación quirúrgica entre los alumnos, superando a los métodos tradicionales y virtuales.
Conclusión: los 3DPLM mejoran la precisión de la planificación quirúrgica, modifican las estrategias y mejoran los resultados educativos en las resecciones hepáticas complejas. A pesar de los impactos mixtos en los resultados intraoperatorios, su utilidad en la planificación y educación preoperatoria es evidente, lo que justifica una mayor exploración.

Palabras clave: Impresión 3D; Neoplasia Hepática; Resección Hepática; Imágenes Tridimensionales; Tomografía; Rayos X Computarizados (TC).

INTRODUCTION

Globally, liver cancer ranks third in terms of cancer-related fatalities and is one of the most frequently diagnosed cancers.[1,2] There is a large mortality and illness burden associated with its expected acceleration in worldwide incidence. For patients with sufficient healthy liver reserves, surgical resection is the most often used radical therapy for liver cancer.[3,4] The intricate structure of the liver and the considerable anatomical diversity across individuals make precise preoperative planning essential for a successful resection.[5] For instance, there may be many common variations in the hepatic vasculature. The hepatic arteries, portal veins, and biliary tree may all exhibit structural variation, in addition to the three to four separate variations seen in each of the right, middle, and left hepatic veins.[6] Due to the increased intricacy of the spatial interactions among intrahepatic structures, customized and adaptive surgical approaches are needed. Tumors must be removed with a sufficient margin to avoid recurrence, and a significant future liver residual must be maintained throughout the procedure.[7] This calls for a thorough comprehension of the spatial interactions between a patient's malignancy and hepatic structure both before and after surgery.[8] The growing inclination towards laparoscopic resection techniques that limit the operative field overview underscores the significance of this comprehension.[9]

When it comes to preoperative planning for liver cancer resection (LCR), computed tomography (CT) and magnetic resonance imaging (MRI) are essential.[10] Because CT offers high-spatial-resolution, three-dimensional (3D) information, it has historically been most often used in research for hepatic structure segmentation and image processing. Due to its excellent contrast-to-noise ratio and ability to provide a clinical diagnosis without the need for contrast material, MRI has also been used for liver imaging more often in recent years. With these modalities, the surgeon must mentally piece together a three-dimensional (3D) visualization of the liver and its constituent parts from a sequence of two-dimensional (2D) pictures.[11] The intricate anatomical structure of the liver and the intricate spatial interactions among its intrahepatic components may make this especially difficult.[7] Although they make these linkages easier to understand, three-dimensional virtual reconstructions (3DVRs) still require the surgeon to mentally recreate spatial position and depth information from a 2D picture.[12] With the development of patient-specific 3D-printed liver models (3DPLMs), 3D printing advances might potentially ease these challenges.[13] Layer by layer, 3D things are created using 3DP, a kind of additive manufacturing, from a digital file. Medicine now employs a number of 3DP technologies, all of which begin with the selective deposition of a liquid, powder, or filament material that is then fused layer by layer using light, heat energy, or a bonding agent to create a solid material.[14] To print representative 3DPLMs, segments of each patient's unique liver architecture and pathology from their medical imaging data may be recreated in 3D file formats compatible with 3DP.[9]

Previous reviews of the literature by Perica and Sun[13], Witowski et al.[15], and Timothy Rossi et al.[16], highlight the value of 3DPLMs for surgical planning; however, there is a dearth of systematic research that examines whether or not 3DPLMs improve surgical planning for LCR patients or their intra- and postoperative outcomes and also no evidence is present that compares it with traditional methods. In light of this, this review aims to further the body of knowledge on 3DPLMs by offering a current and critical analysis of their applicability for surgical planning and intraoperative guiding of LCR in comparison to traditional methods, as well as an investigation into whether or not these uses lead to better patient outcomes.

METHOD

Study Design

This systematic review evaluated the outcomes of 3D printing-assisted surgical planning compared to traditional methods in complex liver resections. The review focused on studies that assessed surgical planning accuracy, surgical strategy modification, surgical outcomes and complications, detection and identification of anatomical structures, and educational value and training effectiveness in 3D printing technology.

Sample Selection

The objective of the search strategy was to systematically identify relevant research on the outcomes of 3D printing-assisted surgical planning versus traditional methods in complex liver resections. The search was conducted using a combination of keywords and Medical Subject Headings (MeSH) terms in databases such as PubMed, Embase, and Web of Science. The search terms included “3D printing,” “3D printed models,” “liver resection,” “complex liver surgery,” “traditional surgical planning,” “CT,” “MRI,” “surgical outcomes,” and “educational value.” Boolean operators (AND, OR) were used to refine the search and ensure comprehensive coverage of relevant studies.

Inclusion Criteria

- Studies that compared 3D printing-assisted surgical planning with traditional methods in the context of complex liver resections.
- Research articles published in English.
- Studies involving human subjects, including patients and medical professionals.
- Publications from January 2018 to August 2024.
- Articles published in peer-reviewed journals.
- Studies that provided clear methodologies and data on surgical planning, surgical strategy modification, surgical outcomes, detection of anatomical structures, and educational or training effectiveness.

Exclusion Criteria

- Review articles, meta-analyses, editorials, letters, case reports with one patient and conference abstracts.
- Studies focusing solely on 3D printing technology without comparing it to traditional surgical planning methods.
- Studies not specifically examining complex liver resections.
- Studies with insufficient or unclear methodologies and data.

Study Method

An electronic search of relevant databases was performed, and the initial selection of studies was based on the review of titles and abstracts. Full texts of selected articles were subsequently assessed for eligibility according to the predefined inclusion and exclusion criteria. Studies that met all inclusion criteria were included in the systematic review.

A total of 11 studies were ultimately included in the systematic review after thoroughly evaluating the full texts.

Data Extraction

Data were extracted from the included studies using a standardized form. Key information such as author(s), publication year, study design, population type and number, intervention (3D printing-assisted planning), comparative traditional methods, outcomes assessed (e.g., surgical accuracy, strategy modification, outcomes, and educational value), and results with statistical analysis were systematically recorded.

Data Analysis

The results of the included studies were synthesized both qualitatively and quantitatively. Descriptive analysis was performed to summarize the findings related to key outcome categories such as surgical planning accuracy, surgical strategy modification, surgical outcomes and complications, detection and identification of anatomical structures, and educational value and training effectiveness. To quantify the accuracy of planning and detection of lesions, a pooled analysis was conducted using both fixed and random effects models. Statistical heterogeneity among studies was assessed using the I^2 statistic, with values greater than 50 % indicating substantial heterogeneity.

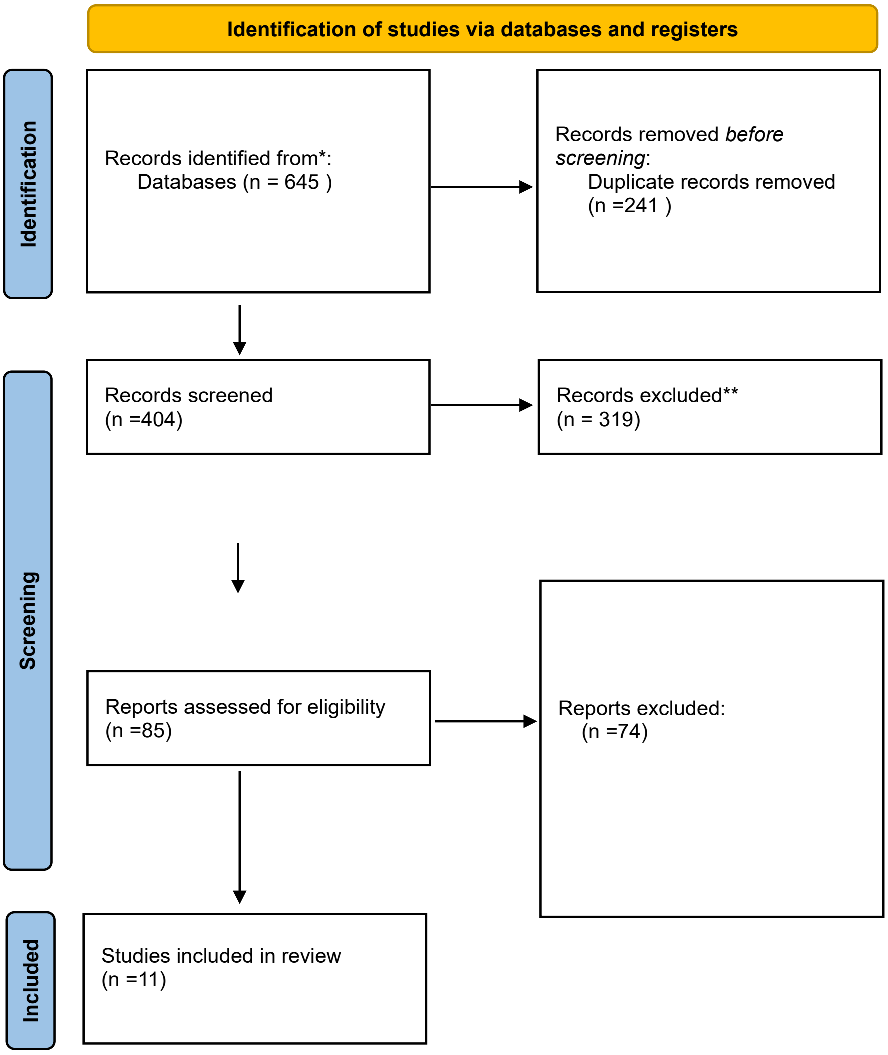

Figure 1. PRISMA Flow Diagram

RESULTS

645 publications in all were found during the first literature search. Following a meticulous assessment of abstracts and titles, 85 articles were deemed relevant, and their full texts were acquired for further examination. Excluded studies did not fulfil the inclusion criteria or did not explicitly investigate outcomes of 3D printing-assisted surgical planning versus traditional methods in complex liver resection. After a thorough screening procedure, ten papers were found to be appropriate for the systematic review.

Study characteristics

A review of eleven papers on the use of simulation and 3D printing in liver surgery was conducted. A variety of study types were used in the research, including randomized controlled, prospective, experimental, preclinical comparison, randomized pilot, randomized observational, prospective, and retrospective studies.

There was a substantial variation in the participant groups, ranging from 305 individuals in some trials to as few as 8 patients in others. A smaller number of studies covered a larger patient population with illnesses such as hepatobiliary tumors or liver malignancies, while other research concentrated on specialized groups such as surgical residents (n = 45) or interns (n = 62).

A variety of outcomes were evaluated in the research, such as patient satisfaction, surgical planning accuracy, model accuracy, liver lesion detection rates, and educational efficacy. Comparisons were done between typical 2D imaging, virtual reality (VR) models, 3D printed models, and other simulation techniques. The intervention approaches also differed. A variety of imaging approaches and methods were used, including Multi-Detector Computed Tomography (MDCT), 3D printing (3DP), 3D virtual reconstruction, and several instructional models. The results showed that, in surgical settings, 3D printed models often enhanced comprehension and planning accuracy, with noteworthy advantages for preoperative training and patient education. The influence on surgical outcomes and cost-effectiveness varied throughout research, the data also showed.

Surgical Planning Accuracy

Significant advantages have been shown by 3D printing in the field of surgical planning. According to Witowski et al. (2020), the use of intraoperative ultrasound (IOUS) in conjunction with 3D printed models resulted in revisions to the surgery plan for 68 % of the 19 patients with liver cancers.[9] Interestingly, the use of 3D models was directly responsible for 26 percent of these alterations, suggesting a significant increase in surgical planning accuracy over conventional 2D imaging techniques. Similarly, Wang et al. (2017) discovered that when used 3D Interactive Quantitative Surgical Planning (IQSP) in place of traditional 2D imaging, 37,4 % of difficult cases showed different surgical plans in a study of 305 patients having hepatectomy.[17] With a 92,1 % alignment in anatomic hepatectomy, 3D IQSP clearly improved surgical plan accuracy, demonstrating its outstanding precision. Furthermore, in randomized controlled trial with 62 interns, Cheng et al. (2023) discovered that the use of 3D printed models (3DPM) led to substantially higher scores in tumor site identification—mean scores of 36,7 vs 33,2 for 3DVR and 26,8 for MDCT.[18] This implies that the comprehension of liver architecture is much enhanced by 3DPM, which results in more precise surgical planning. In an experimental study involving 45 surgical residents, Yang et al. (2018) further demonstrated the efficacy of 3D printing by showing that, in comparison to virtual 3D reconstruction and MDCT, 3D printed models significantly improved tumor location assignment accuracy and facilitated faster, more precise surgical resection proposals.[12]

Surgical Strategy Modification

Moreover, 3D printing is essential for changing surgical tactics. According to Witowski et al. (2020), 68 % of instances including the use of 3D printed models in conjunction with IOUS resulted in modifications to the surgical approach, highlighting the significance of this technique in improving surgical planning.[9] In line with this, Cheng et al. (2022) found that 16,7 % of patients in their research experienced a modification in their surgical approach while using 3D printing technology in conjunction with indocyanine green (ICG) fluorescence navigation; by contrast, this was not the case for any patients in the group undergoing standard laparoscopic hepatectomy.[19] This suggests that while 3D printing did not substantially influence short-term surgical results, it may help pick the best surgical techniques, particularly when combined with ICG.

Surgical Outcomes and Complications

Li et al. (2021) presented evidence that 3D printing-assisted laparoscopic resection is a safe and successful surgical procedure in terms of surgical outcomes.[20] The mean surgery time in their investigation of eight patients with liver cancer was 216±41 minutes, with an average blood loss of 75 mL and no reported intraoperative problems. During a median follow-up of 12,5 months, there was only one incidence of tumor recurrence, indicating that 3D printing technique is practical and does not present any substantial problems. Cheng et al. (2022) observed that while the combination of 3D printing with ICG navigation facilitated the change of surgical strategies, no noteworthy distinctions were seen in terms of operating time, blood loss, or postoperative outcomes when compared to traditional laparoscopic techniques.[11]

Detection and Identification of Anatomical Structures

Personalized 3D-printed transparent liver models significantly increased the detection rates of focal liver lesions (FLLs), according to research by Joo et al. (2019).[21] Their research showed that with 3D models, the detection rate was 99,0 %, whereas with standard techniques, it was 82,7 %. Of the extra FLLs, especially those ≤10 mm, were found. Better pathology matching and tumor staging result from this improved detection capabilities. Huettl et al. (2020) evaluated the efficacy of 3D PDFs in a preclinical investigation by contrasting virtual reality (VR) with physical 3D printed models (PR).[22] They discovered that compared to conventional techniques, both VR and PR models produced more accurate tumor assignments and faster processing times, which improved anatomical orientation.

Educational Value and Training Effectiveness

It has also been shown that 3D printing is beneficial in educational settings. In a multicenter investigation including 35 patients with complicated hepatobiliary malignancies, Lopez-Lopez et al. (2020) discovered that 3D printed models had a strong association (a Dice Similarity Coefficient of 0,92) with CT/MRI and surgical specimens.[23] These models did not always have an impact on surgical results, but they were helpful for planning procedures and for teaching purposes. In a randomized pilot study, Giehl-Brown et al. (2023) showed that using 3D liver models in surgical education increased patient satisfaction: 80 % of patients expressed pleasure, compared to 55 % in the group receiving standard patient education.[24] In addition, patients were more knowledgeable about the surgical process, their condition, and any possible side effects. In addition, Cheng et al. (2023) discovered that, in comparison to 3DVR and MDCT, 3D printed models greatly increased interns' pleasure and interest in liver anatomy and surgical planning.[18] In a similar vein, Yang et al. (2018) found that, in comparison to virtual reconstruction and MDCT, 3D printing greatly enhanced surgical residents' comprehension of liver anatomy and allowed for quicker and more precise surgical planning.[12]

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Table 1. Characteristics and results of the studies reviewed

Author(s)	Year	Study Design	Population Type and Number	Intervention	Comparative Traditional Method	Outcomes Assessed	Results with Stats	Conclusion
Witowski et al.[9]	2020	Prospective Observational Study	19 patients with liver malignancies	3D printed models with IOUS	Traditional 2D imaging (CT)	Changes in surgical approach; surgical planning accuracy	68 % of patients had changes in surgical plan; 26 % preoperative changes due to 3D models; 47 % changes due to IOUS	3D printing is a valuable adjunct to IOUS for complex laparoscopic liver resections, influencing surgical planning in a significant number of cases.
Wang et al.[17]	2017	Prospective Study	305 patients undergoing hepatectomy	3D Interactive Quantitative Surgical Planning (IQSP)	Traditional 2D imaging (PACS)	Accuracy and predictability of surgical plans; resection volumes	37,4 % of complex hepatectomy cases had differing plans between 2D and 3D IQSP; IQSP improved plan accuracy with 92,1 % alignment in anatomic hepatectomy	3D IQSP improves the accuracy and predictability of surgical plans, leading to more radical and safer liver resections compared to traditional methods.
Lopez-Lopez et al.[23]	2020	Multicenter Study	35 patients with complex hepatobiliary tumors	3D printed models	CT/MRI	Model accuracy; teaching and planning effectiveness	3D models showed good correlation with CT/MRI and surgical specimens; Dice Similarity Coefficient was 0,92; positive feedback rate of 0,89	3D hepatic models have good correlation with imaging and pathology and are useful for education and surgical planning, but do not necessarily affect surgical outcomes.
Joo et al.[21]	2019	Prospective Study	20 patients with multiple FLLs	Personalized 3D-printed transparent liver models	Routine protocol	Detection rates of focal liver lesions (FLLs)	99,0 % detection rate using 3D models vs. 82,7 % with routine protocol; 23,9 % additional FLLs detected in lesions ≤10 mm	Personalized 3D-printed liver models improve detection of small focal liver lesions, leading to better pathological matching and tumor staging.
Giehl-Brown et al.[24]	2023	Randomized Pilot Trial	40 patients undergoing hepatobiliary surgery	3D liver model-enhanced surgical education	Regular patient education	Patient satisfaction; understanding of surgical procedure	3D-LiMo group had higher satisfaction (80 % vs. 55 %), better understanding of disease and procedure, and enhanced awareness of complications	3D-printed liver models enhance patient satisfaction and understanding of the surgical procedure, facilitating better preoperative education.
Cheng et al.[18]	2023	Randomized Controlled Study	62 interns	3D printed models (3DPM), 3D virtual reconstruction (3DVR), MDCT	3DVR, MDCT	Interns' test scores; satisfaction and interest	3DPM group scored higher: tumor location (3DPM vs. 3DVR, MDCT: 36,7 vs. 33,2, 26,8, P=0,03, P<0,01); tumor-vessel relationship (37,1 vs. 31,6, 30,0, P<0,01, P<0,01); surgical planning (8 vs. 4,9, 5,9, P<0,01, P=0,04)	3DPM significantly improves interns' understanding of liver anatomy and surgical planning, leading to higher satisfaction and interest compared to 3DVR and MDCT.

Cheng et al.[11]	2022	Retrospective Study	54 patients with complex hepatobiliary diseases	3D printing technology + indocyanine green (ICG) fluorescent navigation	Conventional laparoscopic hepatectomy	Surgical strategy modification; operating time; blood loss; outcomes	16,7 % of patients had modified surgical strategy in 3DP+ICG group vs. none in the conventional group (P=0,02); no significant differences in operating time, blood loss, or postoperative outcomes	3D printing combined with ICG navigation aids in selecting optimal surgical strategies but does not improve short-term outcomes.
Yang et al.[12]	2018	Experimental Study	45 surgical residents	3D printed models (3DP), virtual 3D reconstruction (VIR), MDCT	VIR, MDCT	Tumor location assignment accuracy; time spent; resection proposals	3DP group: mean score 80,92, time 93s; VIR group: mean score 55,25, time 223s; MDCT group: mean score 34,50, time 286s. The mean accuracy of the surgical resection proposal for 3DP, VIR, and MDCT was 57, 25, and 25 %, respectively.	3D printing significantly improves understanding of liver anatomy, facilitating faster and more accurate surgical planning.
Huettl et al.[22]	2020	Preclinical Comparison Study	30 participants (students, residents, fellows, experts)	3D printed models (PR), virtual reality (VR) 3D models, 3D PDFs	3D PDFs	Anatomical orientation; tumor segment assignment; time spent	VR and PR models led to more correct tumor assignments and shorter times compared to 3D PDFs (P<0,001 for time)	VR and PR models improve anatomical orientation better than 3D PDFs; VR was preferred by users for its functionality.
Li et al.[20]	2021	Retrospective Descriptive Study	8 liver cancer patients	3D printing technology assisted laparoscopic resection of segment 8	Standard laparoscopic resection	Surgical time; blood loss; postoperative complications; tumor recurrence	Mean operation time 216±41 min; blood loss 75 mL; no intraoperative complications; 1 recurrence in follow-up (12,5 months median)	3D printing technology-assisted laparoscopic resection is safe, feasible, and effective with no significant complications.
Arnau Valls-Esteve et al.[14]	2024	Retrospective study	3 pediatric cases	Patient-specific 3D-printed liver tumor simulators	Traditional simulation methods (animal, ex vivo, VR)	Accuracy of anatomical replication; cost-effectiveness; surgical planning and training efficacy	3D simulators showed high anatomical accuracy; cost-effective compared to other models; effective for pre-surgical planning and training.	3D-printed soft models are accurate, cost-effective, and valuable for pre-surgical planning and hands-on training in complex liver surgeries.

The pooled analysis of three studies evaluating the accuracy of planning and detection of lesions using 3D printing-assisted surgical planning demonstrated a high overall proportion of accuracy. The fixed effect model estimated an accuracy proportion of 0,8686 (95 % CI: 0,8156 to 0,9081), while the random effects model showed a slightly higher proportion of 0,9231 (95 % CI: 0,7761 to 0,9765). However, significant heterogeneity was observed among the studies (I^2 = 84,0 %, τ^2 = 0,9151, p < 0,01), indicating variability in the effect sizes across the studies. Despite the heterogeneity, the random effects model suggests a strong overall accuracy, supporting the effectiveness of 3D printing in enhancing surgical planning and lesion detection.

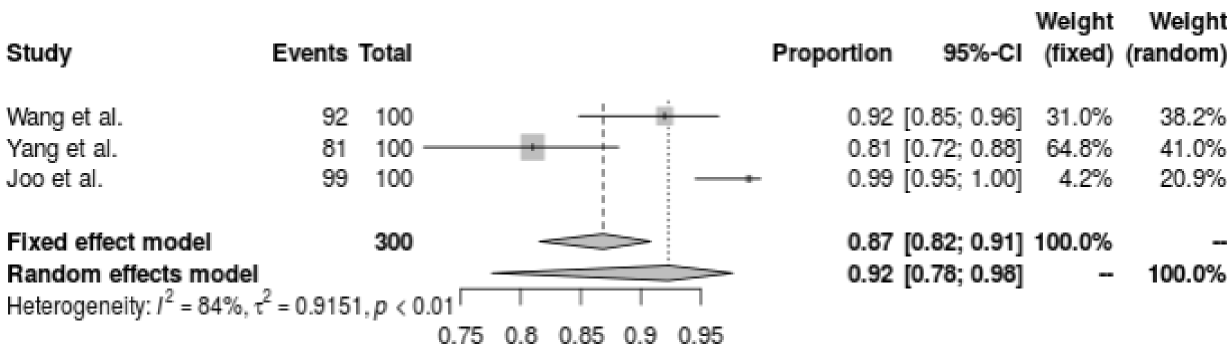

Figure 2. Forest plot of accuracy

DISCUSSION

The use of 3D printing in surgical planning has shown to have major benefits over conventional techniques, especially in complicated liver resections. A comprehensive analysis of several research shows that 3D printing increases surgical planning accuracy while also improving anatomical structure recognition and identification, adjusting surgical techniques, and providing useful instructional material for medical students.

Conventionally, CT and/or MRI scans of the patient are used to guide LCR surgical planning. The surgeon determines suitable resection planes and techniques for vascular/biliary reconstruction using 3DVRs and 2D axial/multiplanar images. For this, a 2D screen's visuals must be used to create a 3D mental representation of the complex liver architecture of the patient. This task can be made easier by 3DPLMs, which offer a tactile, manipulable, transparent, color-coded, and highly cognizable representation of the liver anatomy of each patient.[19,25] This improves understanding of the intricate and highly variable 3D spatial relationships between intrahepatic structures and improves cognitive localization of liver tumors.[20] Surgeons may choose the best surgical methods, resection planes, and vascular reconstruction techniques with the use of their enhanced anatomical perception.[16]

The increase in surgical planning accuracy using 3D printed models is one of the most important outcomes from many research. The integration of 3D printing with other sophisticated imaging methods resulted in revisions to the surgery plan for a significant number of patients, as noted by Witowski et al.[9] (2020) and Wang et al.[17] (2017). These changes were often brought about by the 3D models' greater anatomical vision, which, as compared to conventional 2D imaging, enabled for more accurate surgical planning. This is in line with the findings of Cheng et al.[18] (2023) and Yang et al.[12] (2018), who found that, especially for medical trainees, 3D printed models greatly increased comprehension and accuracy in locating tumors and organizing resections. These conclusions are further supported by the pooled analysis, which shows that 3D printing-assisted planning yields a high overall percentage of correctness. The accuracy percentage of the random effects model was 0,9231 (95 % CI: 0,7761 to 0,9765), highlighting the potential of 3D printing to improve surgical planning precision. The found considerable heterogeneity (I^2 = 84,0 %, p < 0,01) implies that the outcomes of 3D printing might differ based on particular elements including the intricacy of the cases, the surgical team's expertise, and the particular 3D printing technology used.

Apart from enhancing precision in planning, 3D printing exhibits potential in directing adjustments to surgical tactics. The capacity to see intricate anatomical features in three dimensions enables surgeons to more accurately evaluate the viability of different surgical techniques. For example, Cheng et al. (2022) discovered that the combination of indocyanine green (ICG) fluorescence navigation and 3D printing resulted in 16,7 % of patients having their surgical approach modified, highlighting the technique's potential to impact intraoperative decision-making.[11] This adjustment shows the strategic benefits that 3D printing may give in designing more radical and safer resections, even while it did not significantly alter short-term results like operating time or blood loss.

Research on the efficacy and safety of procedures aided by 3D printing has also shown encouraging findings.

According to Li et al. (2021), laparoscopic resection aided by 3D printing was not only possible but also produced few intraoperative problems and positive follow-up results.[20] These results imply that 3D printing does contribute to a safe surgical procedure with a low incidence of problems, even if it may not significantly shorten operating times or decrease blood loss. But as Cheng et al. (2022) point out, there are no appreciable variations in the short-term results between traditional and 3D printing-assisted techniques.[11] This suggests that further studies are necessary to completely comprehend the long-term effects of 3D printing on surgical outcomes.

Another important advantage of 3D printed objects is their improved capacity for detection. According to Joo et al. (2019), customized 3D-printed liver models greatly increased the detection rates of focal liver lesions (FLLs), particularly tiny lesions that are often difficult to detect with conventional imaging methods.[21] Planning the appropriate therapy after tumor staging depends on this enhanced detection. Huettl et al. (2020) discovered that the combination of 3D printing with virtual reality models enhanced anatomical orientation and tumor segment assignment, resulting in surgical planning that was more precise and effective.[8] In addition to its immediate therapeutic uses, 3D printing has shown to be an effective teaching and training aid for physicians. Research by Lopez-Lopez et al.[23] (2020), Giehl-Brown et al.[24] (2023), and Cheng et al.[18] (2023) repeatedly shown that 3D printed models improved medical students', residents', and patients' comprehension of liver anatomy and surgical procedures. These models enhanced enjoyment and confidence in comprehending intricate anatomical linkages in addition to improving educational outcomes like test scores and surgical planning accuracy. These models provide a particularly useful hands-on experience in a training scenario, where manipulating and seeing 3D organ representations may greatly improve learning and retention.

The variation in design, sample size, and outcome measures across the included studies is a noteworthy limitation of this review, since it complicates direct comparisons and pooled analysis. Furthermore, weakening the evidence's robustness are the few numbers of randomized controlled trials and the overwhelming amount of observational research. Examining long-term results is further limited by the short-term follow-up in many research. To evaluate the long-term effect of 3D printing on patient outcomes in liver resections, future research should concentrate on bigger, multicenter randomized controlled studies using standardized procedures. Furthermore, the use of biocompatible materials and real-time simulation in 3D printing technology should significantly improve its usefulness for surgical planning and instruction, indicating the need for further research in this area.

CONCLUSION

This systematic review underscores the significant advantages of 3D printing-assisted surgical planning over traditional methods in complex liver resections, particularly in enhancing surgical accuracy, modifying surgical strategies, improving anatomical detection, and offering substantial educational value. While 3D printed models were found to improve the precision of surgical plans and the identification of anatomical structures, their impact on short-term surgical outcomes, such as operative time and blood loss, was less pronounced. Additionally, the integration of 3D printing into surgical education demonstrated increased understanding and satisfaction among both trainees and patients. Overall, the review supports the use of 3D printing as a valuable tool in liver surgery, with the potential to improve long-term patient outcomes, although further research is needed to solidify its role in clinical practice.

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CONFLICT OF INTEREST

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